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NUMERICAL MODELLING OF GROUNDWATER EXTRACTION SYSTEM TO CONTROL EXCESSIVE WATER LEVEL

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The main objective of this paper was to design groundwater extraction system to control excessive rise in groundwater table. Its theoretical background is intended to be used for Nitra Industrial Park, which is already under construction at northern part of the town of Nitra. For proper construction and operation of the park, there are already proposed 38 groundwater network wells from which optimum pumping rate is required to be designed to keep the groundwater level at required elevation without causing any depletion to the resource. To address this challenge, we applied numerical groundwater modelling system using TRIWACO simulation package. The modelling package utilises finite element method (FEM) that can handle complex aquifer parameters for running quasi three-dimensional groundwater flow model. Based on available hydrological, geological and hydrogeological data numerous simulations were carried out for both - steady state and transient flow conditions.
In order to implement the transient simulation system, a 1000-year instantaneous flood wave (Q_{1000}) was considered. This research paper will present numerical modelling results on design of groundwater extraction system to maintain the groundwater level to required elevation as well as parameters and uncertainties for design purposes.

KEY WORDS: Groundwater extraction, Piezometric head, Pumping rate, Transient simulation, TRIWACO

NUMERICKÉ MODELOVANIE SYSTÉMU ČERPANIA PODZEMNEJ VODY NA REGULOVANIE ZVÝŠENEJ ÚROVNE HLADINY. Príspevok sa zaoberá hydraulickým návrhom zníženia hladiny podzemnej vody v daných hydrogeologických podmienkach priemyselného parku pozdĺž rieky Nitra severne od mesta Nitra. Pre vhodné podmienky na výstavbu a prevádzku priemyselného parku bol navrhnutý systém 38 čerpacích studní, ktoré majú zabezpečovať požadovanú úroveň hladiny podzemnej vody v areáli priemyselného parku. Na riešenie bola použitá numerická metóda konečných prvkov (MKP) prostredníctvom výpočtového balíka TRIWACO. Pri riešení sme vychádzali z geologických podkladov z archívu GÚDŠ, z hydrologických údajov zo základnej pozorovacej siete podzemných vôd SHMÚ (2015b) a neskôr aj z podrobného hydrogeologického prieskumu realizovaného dodávateľskou firmou. Na základe týchto údajov bol zostavený kvázi trojrozmerný model prúdenia podzemnej vody ako v ustálených, tak aj neustálených podmienkach.
Pri realizácii výpočtu neustáleného prúdenia bola uvažovaná návrhová povodňová vlna pri Q_{1000}. Predkladaný príspevok sa venuje výsledkom numerického modelovania navrhnutého hydraulického systému na zníženie hladiny podzemnej vody v podmienkach prechodu tejto povodňovej vlny v koryte rieky Nitra.

KĽÚČOVÉ SLOVÁ: odber podzemnej vody, piezometrická výška, čerpané množstvo, simulácia neustáleného prúdenia, TRIWACO

Introduction

This research paper is conducted on the northern part of the town of Nitra, where groundwater (GW) table is located very close to the terrain. Its theoretical background is intended to be used for Nitra Industrial Park, which is already under construction at the mentioned area. The area of interest is a plain with a mean elevation of approximately 141.5 m a.s.l. The level of groundwater can rise up to 140.5 and 143.0 m a.s.l. during the dry season and extreme climate conditions (flood wave in the Nitra River), respectively. Thus, for implementing any kind of construction in this area, it is essential to analyse the impacts of the GW on the proposed structures. Moreover, as GW is pervasive and vulnerable natural resource, it is also important to understand its complexity and processes for proper management.

During the construction as well as operation of the park, the GW level is required to be below 140.0 m a.s.l. (as requested by the investor). Hence, the TRIWACO simulation package was used to design a the optimum pumping rate from the proposed 38 well systems (Valčo Krejčí, 2015) based on geological, hydrological and hydrogeological data obtained from different companies and institutes. Based on the data obtained, different simulations were performed for both steady-state and transient flow conditions. At the beginning of the simulations, different parameters of the aquifer and the Nitra River were assumed in order to calculate the groundwater head (i.e., the piezometric head). Afterwards, all the available data about the aquifer and the Nitra River was used to simulate the actual piezometric heads. The drainage and infiltration coefficients of the aquifer were determined by comparing different simulations under different conditions. Due to the scarcity of data and the heterogeneity of the hydrogeological parameters with time and space, the created model was calibrated through a proper calibration system, where the computed and measured piezometric heads in the observation well systems are compared.

For the steady-state simulation, the hydrological condition of the Nitra River was artificially increased by 1.7 m in order to reach the expected water level during the rainy season, i.e., approximately 142 m a.s.l. Consequently, the piezometric heads in the area of interest dramatically increased. Based on the results, the pumping rates from the proposed 38 well systems were designed to maintain the required groundwater level. For the transient simulation, a design flood wave (SHMÚ, 2015a) at a discharge of Q_{1000} of the Nitra River was considered. The effect of a flood wave on the groundwater level was examined to design the pumping rates from the proposed well systems. The results of the transient simulation verified that the designed discharge for the steady-state flow is also sufficient to maintain the required piezometric head approximately below 140.0 m a.s.l. during the course of a flood wave.

Methods and data specification

Study area

The study area is located at northern part of the town of Nitra. It is situated between the villages of Lužianky and Dražovce as shown in Fig. 1. Based on its geomorphology, the area of interest is located on the alluvial plain of the Nitra River, which is flat with the collective characteristics of geological structures (Soták, Vlčko, 2015). This Flood plain creates an uneven wide belt in a northwest to southeast direction, where the width of the area is 2,750 m in the north of the town of Nitra, but narrows down to 600 m in the area of the town (Horváth et al., 2015).

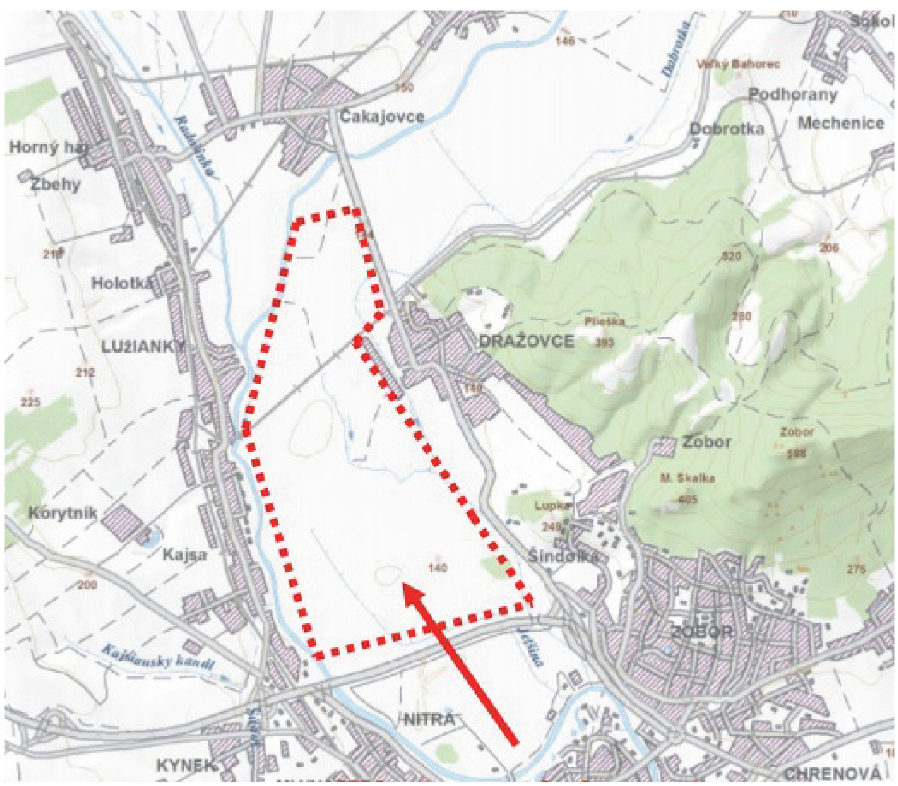

Fig. 1. Location of study area.
Obr. 1. Znázornenie záujmovej oblasti.

Data specification

Only data about the Nitra River were considered as the initial internal boundary conditions. The most necessary data about the Nitra River was obtained from the Slovak Hydrometeorological Institute (SHMÚ, 2015b). For the steady state flow, the average water level for the normal flow was considered. For the transient flow, a design flood wave with a return period of one thousand years (Q_{1000}) was considered, based on the requirements of the investor.
Hydro-geological studies proved that the type of aquifer in the locality is confined; the groundwater is under pressure. The Quaternary gravel-sand, the main part of the aquifer, which collects groundwater is bounded by clay layers from the bottom and the top. The INGEO, Ltd. conducted hydrodynamic tests in 12 pumping and 3 observation wells to analyse the hydraulic conductivity k and coefficient of transmissivity T (Urbaník, 2015). The obtained results are used as input data for simulation of the piezometric heads.

Mathematical background

A partial differential equation, which was derived from an equation of continuity and Darcy's law, is the general equation for the simulation of groundwater flow. This general equation for porous media in terms of a piezometric head can be written as follows (Schwartz, Zhang, 2002):

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z \frac{\partial h}{\partial z}\right)=S_s \frac{\partial h}{\partial t} \qquad (1)$$

where k_x, k_y and k_z are hydraulic conductivities in the x-, y- and z-directions [m.s^{-1}]; S_s is the specific storage [-]; h is the piezometric head [m a.s.l.]; and t is the time [s].

The above equation is a general groundwater flow equation from which any other flow equations can be derived.
If the top of the aquifer is fixed and its change over time is zero, the transmissivity coefficient T is independent of the piezometric head h. This coefficient can be given as:

$$T=k\cdot H \qquad (2)$$

where T is transmissivity coefficient [m^2.s^{-1}]; k is hydraulic conductivity [m.s^{-1}]; and H is the thickness of the aquifer [m].
Based on Boussinesq, an unsteady-state filtration equation in two dimensions can be written as

$$\frac{\partial}{\partial x}\left(T_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_y \frac{\partial h}{\partial y}\right)+W=S_s \frac{\partial h}{\partial t} \qquad (3)$$

where T_x and T_y are transmissivity coefficients [m^2.s^{-1}] in the x- and y-directions; and W is the pumping from/to the point source [m^3·s^{-1}·m^{-2}].

There are different computer-based programs used to solve these equations. In this paper, the TRIWACO simulation package is used to simulate the piezometric head for the mentioned area (Royal Haskoning, 2004). The program uses the finite element method to carry out a simulation of the groundwater flow or head for a quasi three-dimensional modelling system (Velísková, et al. 2014).

Conceptual groundwater model

The TRIWACO program was used to develop the conceptualization process and the modelling of the groundwater for the specified domain. All the physical hydrological, geological and hydrogeological data, which were obtained from different companies and institutions, were used to set the limits of the piezometric head in the domain. Furthermore, river and hills were used as physical features in setting the boundaries of the model. In general, Dirichlet, Neumann and Cauchy boundary conditions were applied to set out the conceptual boundaries of the domain. However, the Neumann boundary condition was predominantly used to establish the boundaries of the model, whereas Cauchy was applied to set the internal boundaries of the model. The Nitra River was considered as the internal boundary conditions of the model, like in (Dušek, Velísková, 2016), for two reasons. Firstly, the Nitra River has a huge impact on the groundwater level at the area of the study. Thus, during the simulation it is easier to use the infiltration and drainage resistance of the river as input data if the river is considered as the internal boundaries of the model. Secondly, during the transient simulation, the parameters of the river changed with almost every time step. This situation could be better applied during the simulation if the river was located within the boundaries of the model. For the steady state simulation, the normal water level of (140.75 m a.s.l.) in the Nitra River was used to set the conceptual model.
In the study area, there are also 55 boreholes (Soták, Vlčko, 2015), which were used as check (control) points. The boreholes have assigned codes with corresponding top and bottom elevation data, which was used for the model's calibration. The hydraulic conductivity of the aquifer, which was determined by a hydrodynamic test, was used to calculate the transmissivity of the aquifer across the boundaries based on Eq (2). Furthermore, INGEO Ltd. Žilina (Urbaník, 2015) estimated the coefficient of storativity from twelve observation and three pumping wells. The estimated values ranged from 4.48×10^{-5} to 9.28×10^{-2} [-]. Those values were used as input data to carry out the transient simulation.
After creating the conceptual model, which is associated

with the calculation grid, the next step was running the model with its code. The conceptual model was used to compile data which were already known about the hydrological and hydrogeological systems; a scheme was then prepared for designing the numerical models. This conceptual model was taken as the parent dataset, and the calculation grid was taken as the discretization dataset, which had already been created for the given model. Therefore, in order to begin the numerical simulation, the created conceptual model was converted to the numerical model with the help of the TRIWACO program. It uses the finite element method of numerical solutions to model groundwater flow or a groundwater head Royal Haskoning (2004), Using the numerical models, the piezometric head was simulated by an approximation of the governing equation at specific locations. The head was calculated at discrete points in space and for specific values of time. The initial piezometric heads were displayed as a contour map from imported data.

Model calibration

Calibration is a process whereby the simulated and measured piezometric heads are automatically compared. All the parameters mentioned before and the data about the observation wells were used to set up the calibration system. The measured groundwater head in the observation wells (BH1 to BH55) and the results of the simulated piezometric heads were compared.

Results and discussion

Steady state simulation

The conceptual model was taken as the parent dataset and the calculation grid was taken as the discretization dataset, which had already been created for the given model. In this groundwater modelling, different simulations are created that use different parameters based on different situations. The first simulation was carried out directly from the conceptual model, and the piezometric head in the boundaries of the model was displayed as a contour map (Fig. 2). All the inherited parameters were not modified at this stage. However, an approximate initial piezometric head, which was closer to the heads to be simulated, was created to speed up the simulation. In this simulation, the activity of the Nitra River was taken into account. The Dobrotka stream is inactive, and there is no available data about the stream. Thus, its impact on the simulation was ignored. Moreover, another two sub-simulations were created under this simulation in order to evaluate whether the interpolation methods did or did not have different results. Nevertheless, the results of the simulation, which were calculated using ordinary methods (i.e., the Triangulated Irregular Network, Kriging or Inverse Distance to a Power method) of interpolation, showed similar results. Thus, the methods of interpolation using the TRIWACO simulation package do not show significant differences in their results.

After the calibration and validation of the input data, the impact of the hydrological situation on the piezometric heads was tested. Therefore, the water level in the Nitra River was artificially increased (as could be expected during the rainy season) by 1.7 m in order to raise the water level to approximately 142.0 m a.s.l. The simulated piezometric heads (Fig. 3) indicate that the groundwater level around the area of interest increased from 140.60 m to 142.35 m a.s.l. The results after this simulation were used to design the pumping rates, which are sufficient to keep the groundwater level below 140.0 m a.s.l. around the area of the park. Simultaneously, other simulations were carried out using the same concept, but with different values for the infiltration and drainage resistance of the river. However, for all the possible combinations of the infiltration and drainage resistance, the simulated piezometric heads were approximately similar within the model boundaries.

As can be seen in Fig. 3, where the water level in the Nitra River was raised by 1.7 m, the groundwater elevations around the area of interest were consequently raised from approximately 140.55 to 142.35 m a.s.l. Based on Darcy's law, the permeability of the river bed and the difference in the heads are directly proportional to the flow rate between the river and the aquifer (Velísková et al. 2014) .Therefore, the above results indicate that there is leakage from the river to the aquifer. However, the investor wanted to keep the elevation of the groundwater below 140.0 m a.s.l. Hence, it was necessary to design a pumping or drainage system to lower the level of the groundwater to an acceptable depth. Based on these results, several simulations were performed to determine the optimum pumping rates from the wells to maintain the required elevation. The simulation, which was carried out considering a constant pumping rate of 1 $l{\cdot}s^{-1}$ from the individual wells, showed that the required piezometric heads were achieved on the eastern part of the area. However, the piezometric heads along the Nitra River were still above 140.0 m a.s.l. As a result, another simulation was performed in the opposite direction (i.e., assuming constant piezometric heads of 139.75 m a.s.l. in the wells) to compute the pumping rates from the well systems. The pumping rates computed for the assumed piezometric heads vary between 0.4 $l{\cdot}s^{-1}$ and 5.0 $l{\cdot}s^{-1}$. Pumping the maximum rate of 5.0 $l{\cdot}s^{-1}$ from the well systems would have a negative effect on the quantity of the groundwater around the area as well as on the Nitra River. Moreover, the maximum pumping rate might also result in the collapse of the well systems. Accordingly, the maximum pumping rate of 2.5 $l{\cdot}s^{-1}$ and minimum pumping rate of 1 $l{\cdot}s^{-1}$ are designed to maintain the groundwater head at the required elevation (Fig. 4). It can be seen from the contour map that the designed pumping rate is satisfactory to assure the required groundwater level in the vicinity of the park.

Transient simulation

For the transient simulation, the design flood wave in the Nitra River was used. This design flood wave at a return period of one thousand years (Q_{1000}) in the Nitra River was determined by SHMÚ, where the flood wave had a total duration of 85 hours with a culminating discharge of 514 $m^3 \cdot s^{-1}$ (SHMÚ, 2015a in: Šoltész et al., 2015) Fig. 5. Using the course of this design flood wave and the last simulation of the steady-state conditions as explained above, the transient simulation was carried out to compute the piezometric heads. From the curve of the design flood wave, the Danish Hydraulic Institute (DHI) (Mišík, 2016) calculated the course of the water level in the Nitra River with respect to the time and stations (i.e., seven stations from K0P0 to K6P6), which were used for the simulations of transient flow. Based on this data, different simulations were conducted to simulate the piezometric heads and also to compare the coefficient of storativity which was determined from the hydrodynamic tests. The contour map and timeseries of the piezometric heads in the 2 points (near the Nitra river and fár from the river) during and after pumping is illustrated in Fig. 6.

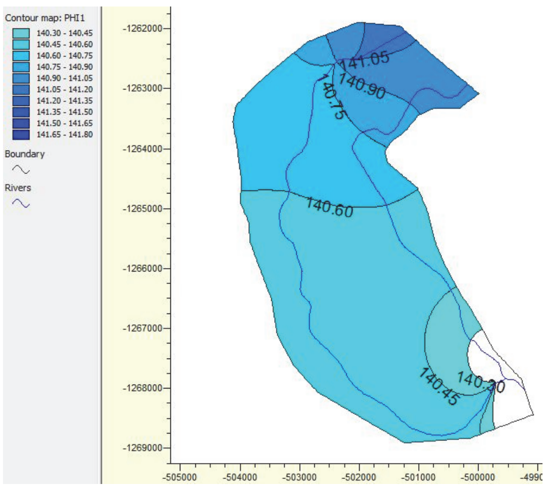

Fig. 2. Simulation results of the piezometric heads (Contour map:PHI) [m a.s.l.] after model calibration
Obr. 2. Výsledky simulácie piezometrickej výšky (Contour map:PHI) [m n. m.] po kalibrácii modelu.

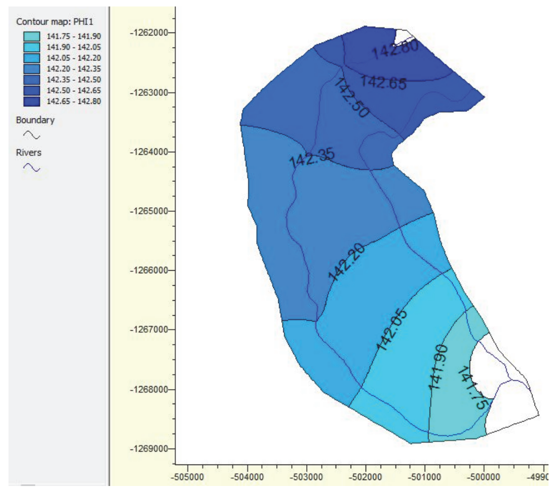

Fig 3. Contour map of the simulated piezometric heads [m a.s.l.] after water level increase in the Nitra River over 1.7 m for a long time.
Obr. 3. Mapa simulovaných izočiar piezometrických výšok [m n. m.] po dlhodobom zvýšení hladiny v toku Nitra o 1,7 m.

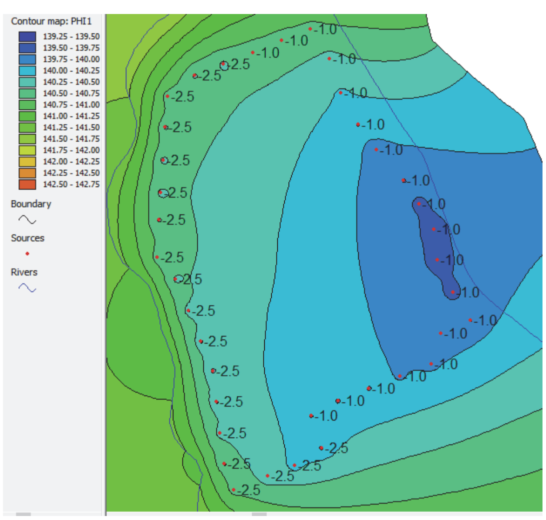

Fig. 4. Designed pumping rates from the individual wells [l·s^{-1}] (detail).
Obr. 4. Navrhované čerpané množstvá z jednotlivých studní [l s^{-1}] (detail).

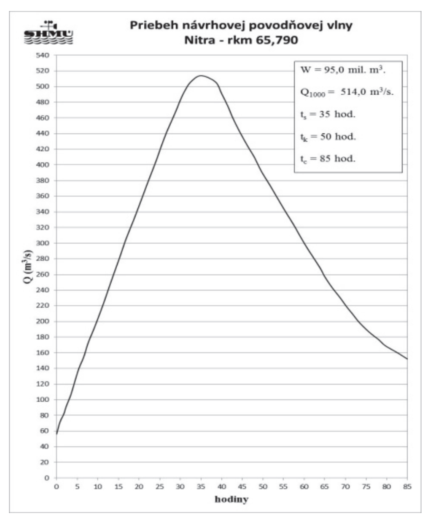

Fig. 5. Designed flood wave at a discharge of Q_{1000} in Nitra River (SHMÚ, 2015a).
Obr. 5. Priebeh návrhovej povodňovej vlny pre prietok Q_{1000} v toku Nitra (SHMÚ, 2015a).

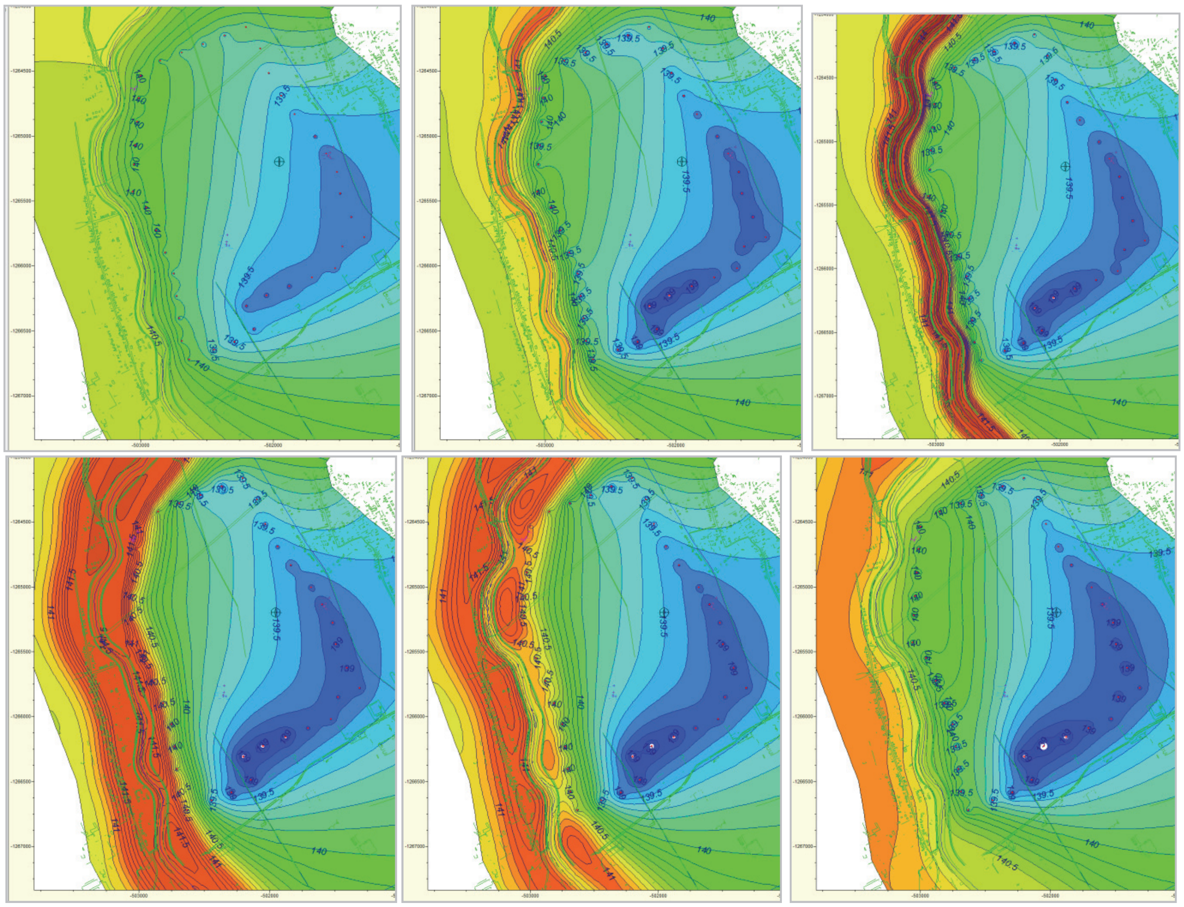

Fig. 6. Simulated contour map of the piezometric heads [m a.s.l.] durng pumping a) 30 days before flood wave, b) at the beginning of flood wave, c) 1. day, d) 4. day, e) 6. day and f) 2 weeks after the flood wave transition

Obr. 6. Simulovaná mapa izočiar piezometrických výšok [m n. m.] počas čerpania a) 30 dní pred prechodom povodňovej vlny, b) na začiatku, c) 1. deň, d) 4. dni, e) 6. dní a f) 2 týždne po prechode povodňovej vlny

Conclusions

The objective of this paper was to design and assess a possible groundwater extraction system based on the TRIWACO simulation package. Several simulations were carried out to evaluate the different parameters and their effect on the outputs. In the model's calibration process, the measured groundwater heads in the observation wells and the results of the simulated piezometric heads were compared. Different simulations demonstrated that the interpolation methods of the parameters did not affect the output of the TRIWACO model.

Increases in the water level of the Nitra River adversely affect the level of the groundwater around the river. The pumping rates from the wells were therefore designed based on the maximum water level in the Nitra River. The values of the calculated pumping rates varied from 5 $l \cdot s^{-1}$ to 0.4 $l \cdot s^{-1}$. However, the optimum pumping rate of 2.5 $l \cdot s^{-1}$ was designed for 16 wells located along the Nitra River, and a rate of 1 $l \cdot s^{-1}$ was designed for the remaining 22 wells. Although the calculated pumping rates have been rounded down to 2.5 $l \cdot s^{-1}$, the elevations of the groundwater heads are still approximately kept to the required elevation of 140.0 m a.s.l.

The results of the transient simulations, which were carried out by considering a Q_{1000} flood wave in the Nitra River, indicated that the piezometric heads in the area of interest suddenly increased within a few hours and gradually decreased to the normal position. However, the designed pumping rate for a steady state flow was enough to assure the required groundwater level for the expected course of the flood wave. In order to operate the pumping system efficiently, the observation wells should be used for regular monitoring of the groundwater level. Based on the information from the observation wells, the pumping system can be switched on or off in order to avoid unnecessary drawdowns in the well systems.

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NUMERICKÉ MODELOVANIE SYSTÉMU ČERPANIA PODZEMNEJ VODY NA REGULOVANIE ZVÝŠENEJ ÚROVNE HLADINY

Predkladaný príspevok sa zaoberá analýzou vplyvu prechodu povodne Q_{1000} na navrhnutý hydraulický systém znižovania hladiny podzemnej vody v lokalite nového závodu Jaguar Land Rover v Nitre. Táto úloha je z matematického hľadiska o to zložitejšia, že sa jedná o proces neustáleného prúdenia ako povrchových, tak podzemných vôd v daných morfologických a hydrogeologických podmienkach a len veľmi ťažko je správne stanoviť pri takejto úlohe okrajové a najmä začiatočné podmienky pre numerické riešenie.

Autori vychádzali najmä z dvoch teoretických podkladov, resp. výpočtov, ktoré boli oficiálne odovzdané objednávateľovi – Slovenskému vodohospodárskemu podniku, š. p. Prvý teoretický podklad, ktorý sme mali k dispozícii bol výpočet postupu návrhovej povodňovej vlny pri prietoku Q_{1000} v toku Nitra pre rkm 65,790, ktorej priebeh bol stanovený SHMÚ (SHMÚ in: Šoltész, Baroková, 2016). Z neho vyplýva, že táto návrhová povodňová vlna má celkové trvanie 85 hodín, z čoho 35 hodín má vzostupný trend a na jeho konci kulminuje pri prietoku 514 $m^3 \cdot s^{-1}$ a približne 50 hodín klesá. Celkový objem vody, ktorý pritečie počas povodne bol SHMÚ stanovený na 95 mil.m^3. Ďalším teoretickým podkladom bola predbežná správa o výpočte špecifického priesaku telesom a podložím ľavej ochrannej hrádze v dvoch profiloch (Hudec, 2016), ktoré vykonali pracovníci Vodohospodárskej výstavby, š. p., TBD pracovisko Bratislava. Výpočty boli zrealizované za predpokladu neustáleného prúdenia vody v rieke Nitra počas priebehu povodňovej vlny pri uvažovaní projektu navýšenia existujúcich hrádzí a výsledkov inžiniersko-geologického prieskumu. K týmto podkladom sme pri výpočte použili navrhnutý hydraulický systém znižovania hladiny podzemnej vody pomocou 38 studní zabudovaných po obvode budúceho automobilového závodu pozdĺž rieky Nitra severne od mesta Nitra, ktorý považujeme z numerického hľadiska za nemenný.

Z hľadiska hladinového stavu podzemnej vody v záujmovom území bol pre daný výpočet uvažovaný východiskový stav, ktorý bol dosiahnutý po znížení piezometrickej výšky navrhnutým systémom 38 studní s čerpaním podľa (Šoltész a kol., 2015). Tento východiskový stav slúžil ako začiatočná podmienka riešenia prúdenia podzemnej vody pri prechode povodňovej vlny podľa SHMÚ. Pri výpočte neustáleného prúdenia podzemných vôd boli rešpektované hydrogeologické parametre tak, ako boli vyhodnotené v správe (Šoltész a kol., 2015).

Výsledky riešenia ukázali, že pri zvolenej hodnote odporu dna rieky Nitra spôsobenej kolmatáciou dna toku dochádza, pri súčasnom čerpaní z radu 38 studní podľa vyššie uvedeného návrhu, ku kulminácii piezometrickej výšky v tesnej blízkosti hranice územia strategického parku oneskorene o 6,5 až 10 dní. Hodnota nárastu piezometrickej výšky je 0,2 až 0,6 m na úroveň 140,20 – 140,60 m n. m. v závislosti od vzdialenosti od toku. Toto je najzávažnejší vplyv, ku ktorému dochádza pri prechode návrhovej povodňovej vlny pri prietoku Q_{1000} v rieke Nitra. Zvýšená úroveň bola zaznamenaná aj v systéme odberných studní, ale to nie je až taký závažný problém, čerpadlá pri plnej kapacite znížia zvýšenú úroveň piezometrickej výšky za dva dni na prijateľnú mieru (t.j. na cca 140,20 m n. m.).

Z vyhodnotenia výsledkov numerickej simulácie je možné záverom konštatovať, že vplyv prechodu povodňovej vlny pri Q_{1000} v rieke Nitra na navrhnutý hydraulický systém znižovania úrovne piezometrickej výšky je nevýrazný.

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